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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

KEVIN JAMES DOLL

ENTITLED THE EFFECT OF ROLL WAVES ON MASS TRANSFER

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE IN CHEMICAL ENGINEERING

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THE EFFECT OF
ROLL WAVES ON MASS TRANSFER

BY

KEVIN J. DOLL

THESIS

for the

DEGREE OF BACHELOR OF SCIENCE

IN

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College of Liberal Art and Sciences

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TABLE OF CONTENTS

Page

FIGUERS

PHOTOGRAPHS

INTRODUCTION

Oxygen absorption in flowing water has many applications in both chemical engineering and environmental studies. In chemical engineering, mass transfer systems such as wetted wall columns are common. Rivers and streams are the most obvious examples in nature of oxygen absorption.

The resistance to mass transfer of a water-oxygen system lies primarily in the liquid phase (1). As a result of this the hydrodynamic characteristic of the liquid phase should have a substantial effect on the rate of oxygen transfer.

Since the system is characterized by high Schmidt numbers the mass transfer is controlled by the flow close to the surface. The surface characteristics are mainly affected by the turbulance in the liquid generated at the gas-liquid interface and at the wall, and by flow fluctuations imposed by waves. This thesis will be concerned with the effect of large amplitude roll waves on the rate of mass transfer to a liquid layer flowing in the bottom of a rectangular channel.

Roll waves are crested surface disturbances that form perpendicular to the fluid flow and travel parallel to it. These turbulent bores move down the channel at a slightly lower velocity than the main stream.

In studies done by Mark McCready and others it was difficult to distinguish between the effect of roll waves and the air flow on mass transfer in gas-liquid flow systems. This work examines roll waves alone, in the absence of an air flow, in order to separate the two effects. An open channel inclined below the horizontal was used. The effect the angle of inclination, flow rate, and roll wave frequency on mass transfer was studied. Since naturally occuring roll waves are so difficult to control a motor driven paddle was used to generate them. Two oxygen concentration probes were placed at the inlet and at the outlet to determine the change in oxygen concentration of the liquid layer.

THEORY

The mass transfer coefficient, K, is defined from a mass balance on a differential element of fluid:

$$-Q\,dc = WK\,(C - C+)\,dl$$

with

Q = Volumetric flow rate

W = Channel width

K = Mass transfer

l = Channel length

C = Measurable concentration of oxygen

C+ = Equilibrium concentration of oxygen

Rearranging terms gives:

$$\frac{Q}{W}\frac{dc}{(C-C+)} = -K\,dl$$

After integrating one obtains:

$$K = \frac{Q}{Wl}\ln\frac{(C-C+)\text{ inlet}}{(C-C+)\text{ outlet}} \qquad (1)$$

From dimensional reasoning, for a fully developed field, K is proportional to V*, ν, M, u, and the wave properties where ν is the kinematic viscosity, M is the film thickness and u is the flow velocity. I have chosen to represent this relation in terms of the following dimensionless groups:

K/V*, which is a function of Sc, M+ and wave properties, where the Schmidt number, Sc, is defined as:

$$Sc = \frac{\nu}{D}$$

with D = Molecular diffusivity and M+ which is defined as:

$$M+ = \frac{M\,V^*}{\nu} \qquad (2)$$

For the experiments carried out Sc was constant. Therefore I have compared plots of K/V* verses M+ for runs with and without waves in order to exhibit the effect of waves.

The friction velocity, V*, is a function of the shear stress at the wall, τ_w, and the density of the fluid, φ and is given by:

$$V^* = (\tau_w / \varphi)^{\frac{1}{2}} \qquad (3)$$

In a free falling vertical film the wall shear stress is given by:

$$\tau_w = \varphi \, g \, m \qquad (4)$$

Since the component of the force of gravity parellel to an inclined plane is proportional to the sine function of the angle of inclination:

$$\tau = \varphi \, g \, m \sin\theta \quad , \qquad (5)$$

with theta being the angle of inclination of the plane above the horizontal and g being the acceleration of gravity. Substituting equation 5 into equation 3 provides an equation allowing the friction velocity to be calculated:

$$V^* = (m \, g \sin\theta)^{\frac{1}{2}} \qquad (6)$$

From equation (6) and the definition of M+:

$$M+ = \frac{(g \, m^3 \sin\theta)^{\frac{1}{2}}}{\nu} \qquad (7)$$

The following relation between M+ and Re has been developed by Dukler and Bergelin (1):

$$Re = M+ \, (3.0 + 2.5 \ln (M+)) - 64 \qquad (8)$$

The Reynolds number, Re, is the ratio of inertial forces to viscous forces and is given by:

$$Re = \frac{Q}{W \nu} \qquad (9)$$

After measuring the volumetric flow rate and calculating the Reynolds number the two parameters M and M' may be obtained by a trial and error solution of equations 7 and 8.

EXPERIMENTAL

The data used to calculate the mass transfer coefficients were obtained by measuring the change in oxygen concentration of a water stream flowing down the inclined channel shown in table 1.

The aluminum channel was 23.5 feet long, 4.5 inches wide, and 2.5 inches high. It was mounted on 5 unistrut sections, each 5 feet apart with rubber strips between the channel and brackets. Hook bolts were used to attach the channel to the brackets and keep it level.

The water flowed through a rotameter mounted on the wall into the inlet box, down the channel, into the outlet box and then out to the house drains. Both the inlet and outlet boxes were modeled after the design used by Brock (2) and fabricated by Bach and Kratochwill (3).

The waves were generated by connecting a paddle to an electric motor fitted with a cam mechanisim as shown in photographs 1 & 2. The connection was made by running the arm of the paddle from the inlet box through a brass ring that acted as a fulcrum and connecting it to another brass rod leading to the cam mechanisim. This design was adapted by the author from a design by Brock (2). The motor was powered by a variable voltage D.C. Power Supply.

The oxygen concentration measurements were made with a Beckman Fieldlab Oxygen Analyzer number 100801 and two Beckman 39553 oxygen sensors. The sensor was screwed into an epoxy flow-through cell equipped with a needle valve, bulb, two quick acting switches and a thermometer. This network designed by Henstock (4) allows starting of the flow and elimination of most of the trapped air bubbles (see photograph 3). The two electrodes were wired through a switching devise built by Henstock (4) which kept one electrode with a stand-by current through it while the other was registering on the analyzer.

Two twenty-gauge needles were inserted into the channel and sealed with epoxy. The inlet was placed 12 inches from the top and the outlet was placed 1 inch from the bottom. The water flowed through the needles, into twenty gauge tubing and through the cells where its oxygen concentration was measured.

The technique of measuring the concentration consisted of four basic steps. After allowing the instruments to warm up for two hours (non reproducible results were obtained otherwise) the probes were calibrated according to Beckman procedures and then inserted into the cells. First, the rotameter was set on a reading of 20 which corresponds to 4.33 gallons per minute. Then the wave frequency was set by counting the number of cycles the motor went through in 60 seconds. The third step, taken after waiting five minutes for the system to approach equilibrium, involved measuring the inlet concentration. The switching circuit was then set to read the outlet concentration and, after a wait of five minutes, the reading was taken. The procedure was repeated at constant wave frequency at 6.31 gallons per minute, 8.57 gallons per minute and 10.75 gallons per minute.

Using the inlet and outlet concentrations the mass transfer coefficients may be calculated from equation 1. The equilibrium value of the oxygen concentration in water is 10.3 ppm at 14.5 °C. Since the water temperature was constant, C+ was set equal to this value.

From the five different flow rates five Reynolds numbers were computed using equation 8. This allowed the calculation of the film thickness, M, and the dimensionless film thickness, M+ by trial and error using equations 7 and 8. The friction velocity, V*, was then calculated using this value of M in equation 5. Plots of K/V* verses M+ at constant theta and roll wave frequency may be seen in figures 3 through 9.

PRESENTATION OF RESULTS

A. Flow properties of the liquid

Initial work involved the study of the flow characteristics of the liquid with and without generated waves.

The channel was inclined at angles between 3 and 12 degrees. Water flowed down the channel at Reynolds numbers from 2100 to 5200. Roll waves occured to some degree at all Reynolds numbers for inclinations less than 5^{o}. They were present at Reynolds numbers less than 3000 for an angle of 6^{o} and less than 2100 for angle of 7^{o}. No naturally occurring roll waves were observed at any Reynolds number for angles between 8 and 12 degrees. The waves that were generated by the wavemaker were characterized as roll waves. They were slightly crested turbulent disturbances in the flow that formed along the entire width of the channel. The propagation velocity of the waves was dependent only on the Reynolds number and the angle of inclination. Tables 1 and 2 give the measured propagation velocity and the calculated fluid velocity respectively.

When natural roll waves existed in the channel and the wave generator was turned on the natural waves were overcome by the generated ones. Even though this was the case only those angles which produced no natural waves were used. This was done to allow a comparison with and without waves for each angle.

B. Mass transfer results

Once the range of angles was determined the mass transfer data were taken. The results are tabulated in tables 3 through 5 in units of ppm. The film thicknesses were calculated from equations 6 and 7 and are tabulated in table 6 in units of feet. The dimensionless film thicknesses are in table 7. Tables 8 through 11 consist of summaries of all the dimensionless groups that will be correlated.

For each angle of inclination four to six frequencies of roll waves were studied. The average values of K/V^* for each dimensionless film thickness and angle appear in table 12.

DISCUSSION OF RESULTS

A. Flow Characteristics

A.M. Binnie (5) studied roll waves in channels with a lesser degree of inclination, 1-3 degrees. He determined that the wave velocity should be less than that of the bulk fluid. This was found to agree with experiments, as is illustrated in figure 2 which is a plot of bulk velocities, $\bar{u}$, and wave velocity, c, as a function of Re. The wave velocity also is apparently independent of the angle of inclination to within a constant.

B. Mass transfer

Mass transfer rates should be intimately related to the hydrodynamics. Mass transfer not only depends on the mixing involved, but also on the surface area available to it. Mark McCready (6) suggested that perhaps the frequency of the roll waves would have a significant effect on mass transfer. In figures 3 through 9 K/V* vs M+ are plotted as functions of angle of inclination and frequency of roll waves. The data are so scattered, some trend up and others down, that the only conclusion to be drawn is that roll wave frequency has no effect on mass transfer.

The angle of inclination of the channel, however, does seem to show an effect on the mass transfer. K/V* verses M+ is plotted only as a function of the angle of inclination in figure 10. Although the data are scattered, it seems that as the angle increases at a constant M+ the mass transfer decreases. This result could be due to the fact that the fluid will flow faster down a larger incline. Figure 11, the average values of K/V* for all the roll wave frequencies, also shows the decreasing of mass transfer with increasing channel slopes.

In summary the hydrodynamics which affect the mass transfer are in themselves affected by the Reynolds number and the channel slope. The mass transfer is not affected by the roll wave frequency but is a function of the inclination of the channel.

Apparatus for Wave Generation

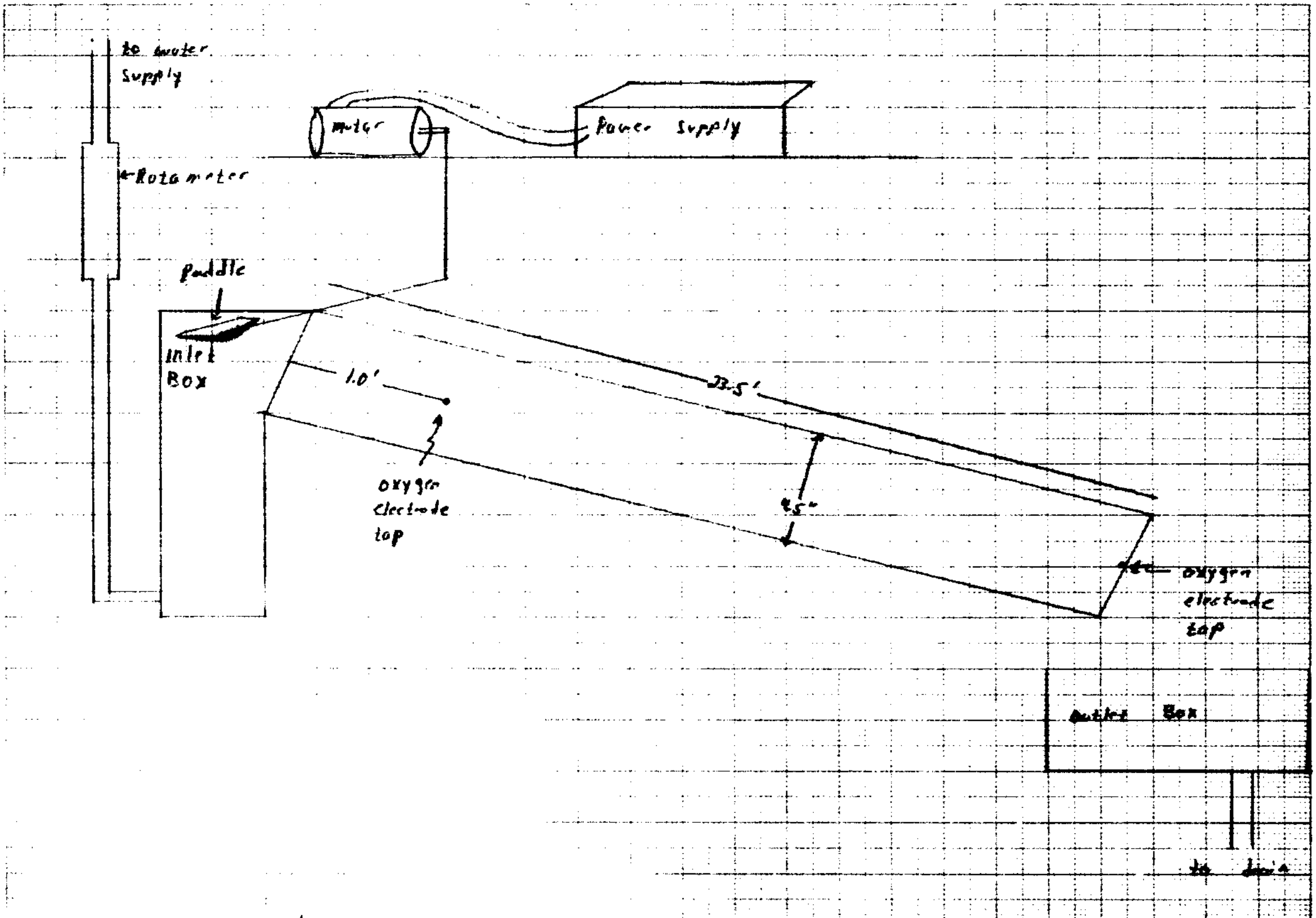


Fig 2

Bulk and Wave Fluid Velocities

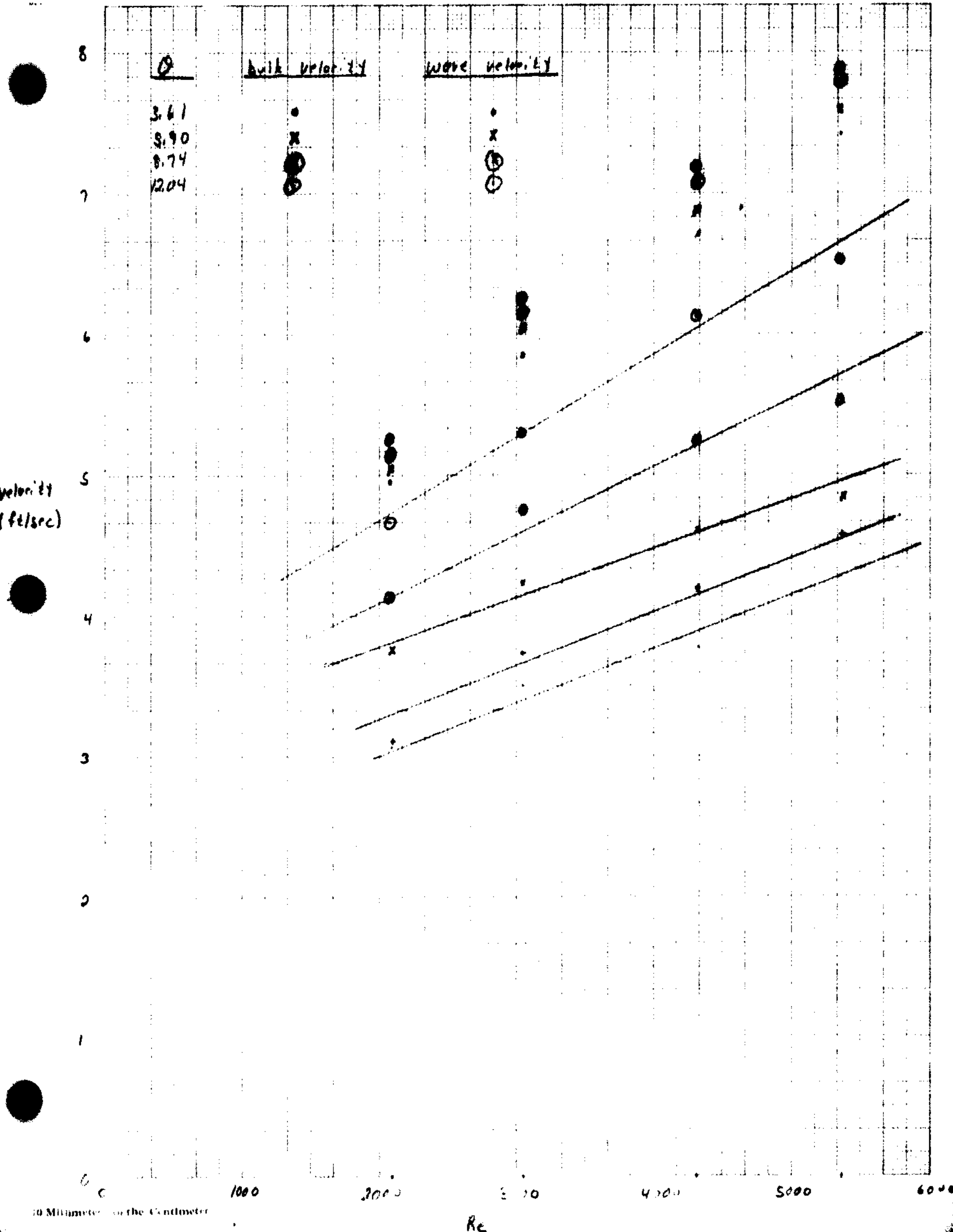


TABLE 1

Table of c (ft/sec) measured, Re, θ

θ	3.614	4.389	5.903	8.738	12.041
Re					
5205	4.28	4.58	4.84	5.54	6.54
4150	3.78	4.20	4.62	5.25	6.13
3056	3.51	3.74	4.24	4.75	5.50
2097	3.07	3.10	3.76	4.16	4.67

TABLE 2

Table at $\bar{u}$ = mean velocity in the film (ft/sec) (Calculated)

θ	3.6414	5.9034	8.1213	8.7380	10.048	12.041
Re						
5205	7.424	7.601	7.692	7.786	7.786	7.882
4150	6.698	6.879	6.973	7.070	7.070	7.170
3056	5.857	6.046	6.145	6.145	6.145	6.248
2097	4.946	5.044	5.144	5.144	5.249	5.249

TABLE 3

O_2 Concentration in PPM

	Re 5205	4150	3056	2097	
$\theta = 812^{\circ}$					
$\nu = 0$ HZ	1.59	1.53	1.54	1.70	IN
	6.60	7.72	7.90	9.48	OUT
$\nu = 7.14$ HZ	1.59	1.60	1.91	1.83	IN
	5.73	6.43	9.49	11.3	OUT
$\nu = 4.39$ HZ	2.02	2.15	2.31	2.48	IN
	7.46	8.20	9.10	10.80	OUT
$\nu = 3.25$ HZ	1.93	2.01	2.21	2.44	IN
	7.09	7.60	9.10	10.50	OUT
$\nu = 1.88$ HZ	1.58	1.75	1.79	1.75	IN
	6.35	6.80	6.57	8.22	OUT

$\theta = 8.12^{o}$

ν	Re	$M \times 10^{2}$ (ft)	V*(ft/sec)	$K \times 10^{3}$ (ft/sec)	M+	K/V*
0	2097	.627	.170	2.69	111	.0158
	3056	.806	.192	2.16	162	.0112
	4150	.988	.213	2.77	220	.0130
	5205	1.150	.230	2.43	275	.0106

ν	$K \times 10^{3}$ (ft/sec)	M+	K/V*	ν	$K \times 10^{3}$ (ft/sec)	M+	K/V*
4.39				1.88	1.62	111	.00953
	3.85	162	.0200		1.37	162	.00714
	3.07	220	.0144		2.02	220	.00948
	3.04	275	0.132		2.25	275	.00978
7.14				3.25			
	3.18	162	.0166		3.68	162	.0192
	2.21	220	.0104		2.54	220	.0119
	1.83	275	.00796		2.72	275	.0118

TABLE 4

O_2 Concentrations in PPM

	Re				
	5205	4150	3056	2097	
$\theta = 10.05^{\circ}$					
$\nu = 0$ HZ	2.02	2.05	1.31	2.26	IN
	5.50	5.88	6.56	6.78	OUT
$\nu = 2.98$ HZ	2.72	2.92	3.07	3.11	IN
	5.65	5.93	6.10	6.53	OUT
$\nu = 1.71$ HZ	2.58	2.45	2.43	2.47	IN
	4.93	5.00	5.18	6.10	OUT
$\nu = 1.39$ HZ	2.89	2.96	2.89	3.05	IN
	5.75	5.97	6.50	7.67	OUT
$\nu = 4.42$ HZ	2.76	2.88	2.95	2.86	IN
	7.11	7.08	7.43	7.62	OUT
$\nu = 7.14$ HZ	302	2.51	258	2.67	IN
	7.10	9.20	10.40	11.60	OUT

$\theta = 10.05^\circ$

ν	Re	$M \times 10^2$(ft)	V*(ft/sec)	$K \times 10^3$(ft/sec)	M+	K/V*
0	2097	.581	.182	.944	110	.00519
	3056	.746	.206	1.46	160	.00709
	4150	.915	.228	1.41	218	.00618
	5205	1.065	.246	1.55	274	.00630

ν	$K \times 10^3$(ft/sec)	M+	K/V*	ν	$K \times 10^3$(ft/sec)	M+	K/V*
1.39	1.16	110	.00637	1.71	.712	110	.00391
	1.11	160	.00540		.716	160	.00348
	1.19	218	.00524		.889	218	.00390
	1.38	274	.00563		1.03	274	.00419
2.98	.738	110	.00406	4.42	1.17	110	.00641
	.905	160	.00439		1.57	160	.00761
	1.19	218	.00520		1.89	218	.00829
	1.39	274	.00564		2.44	274	.00993

ν	Re	$M \times 10^2$(ft)	V*(ft/sec)	$K \times 10^3$(ft/sec)	M+	K/V*
7.14	2097	.581	.182		110	
	3056	.746	.206		160	
	4150	.915	.228	4.43	218	.0194
	5205	1.065	.246	1.86	274	.00756

TABLE 5

O_2 Concentrations in PPM

	Re 5205	4150	3056	2097	
$\theta = 12.04^{\circ}$					
$\nu = 0$ HZ	1.41	1.32	1.19	1.48	IN
	3.[illegible]	3.81	4.52	4.39	OUT
$\nu = 3.12$ HZ	1.56	1.70	1.52	1.56	IN
	3.55	3.70	3.08	3.93	OUT
$\nu = 4.72$ HZ	1.33	1.35	1.32	1.57	IN
	3.32	3.42	3.41	3.83	OUT
$\nu = 5.62$ HZ	1.32	2.15	2.29	2.56	IN
	3.89	4.33	4.78	4.82	OUT
$\nu = 1.66$ HZ	1.87	2.92	2.93	1.99	IN
	3.93	4.09	4.18	5.20	OUT
$\nu = 7.14$ HZ	1.50	1.68	1.89	1.93	IN
	4.91	5.13	6.16	6.28	OUT

$\theta = 12.04^{\circ}$

ν	Re	$M \times 10^2$(ft)	V*(ft/sec)	$K \times 10^3$(ft/sec)	M+	K/V*
0	2097	.544	.193	1.69	110	.00877
	3056	.699	.219	.758	160	.00346
	4150	.857	.242	.735	217	.00304
	5205	.997	.262	.638	272	.00244

ν	$K \times 10^3$(ft/sec)	M+	K/V*	ν	$K \times 10^3$(ft/sec)	M+	K/V*
1.66	.558	110	.00289	3.12	.362	110	.00187
	.310	160	.00141		.326	160	.00149
	.391	217	.00162		.599	217	.00248
	.795	272	.00304		.733	272	.00280
4.72	.342	110	.00178	5.62	.395	110	.00205
	.441	160	.00202		.620	160	.00283
	.595	217	.00246		.704	217	.00291
	.712	272	.00272		.957	272	.00365

ν	Re	$M \times 10^2$(ft)	V*(ft/sec)	K(ft/sec)	M+	K/V*
7.14	2097	.544	.193	.838	110	.00434
	3056	.699	2.19	1.18	160	.00539
	4150	.857	.242	1.16	217	.00478
	5205	.997	.262	1.39	272	.00531

TABLE 6

θ, Re, M

M= Film thickness (ft)

θ / Re	3.6414°	5.9034°	8.1213°	8.7380°	10.048°	12.041°
5205	.0086	.0084	.0083	.0082	.0082	.0081
4150	.0076	.0074	.0073	.0072	.0072	.0071
3056	.0064	.0062	.0061	.0061	.0061	.0060
2097	.0052	.0051	.0050	.0050	.0049	.0049

TABLE 7 M+

Re, θ, M+

Re / θ	2097	3056	4150	5205
3.64	43.7	59.6	77.2	92.9
5.90	54.0	72.4	94.4	114
8.12	61.4	82.8	108	131
8.74	67.6	92.2	119	144
10.05	66.2	89.7	116	143
12.04	72.4	98.1	126	154

TABLE 8

$\theta = 8.12^{o}$

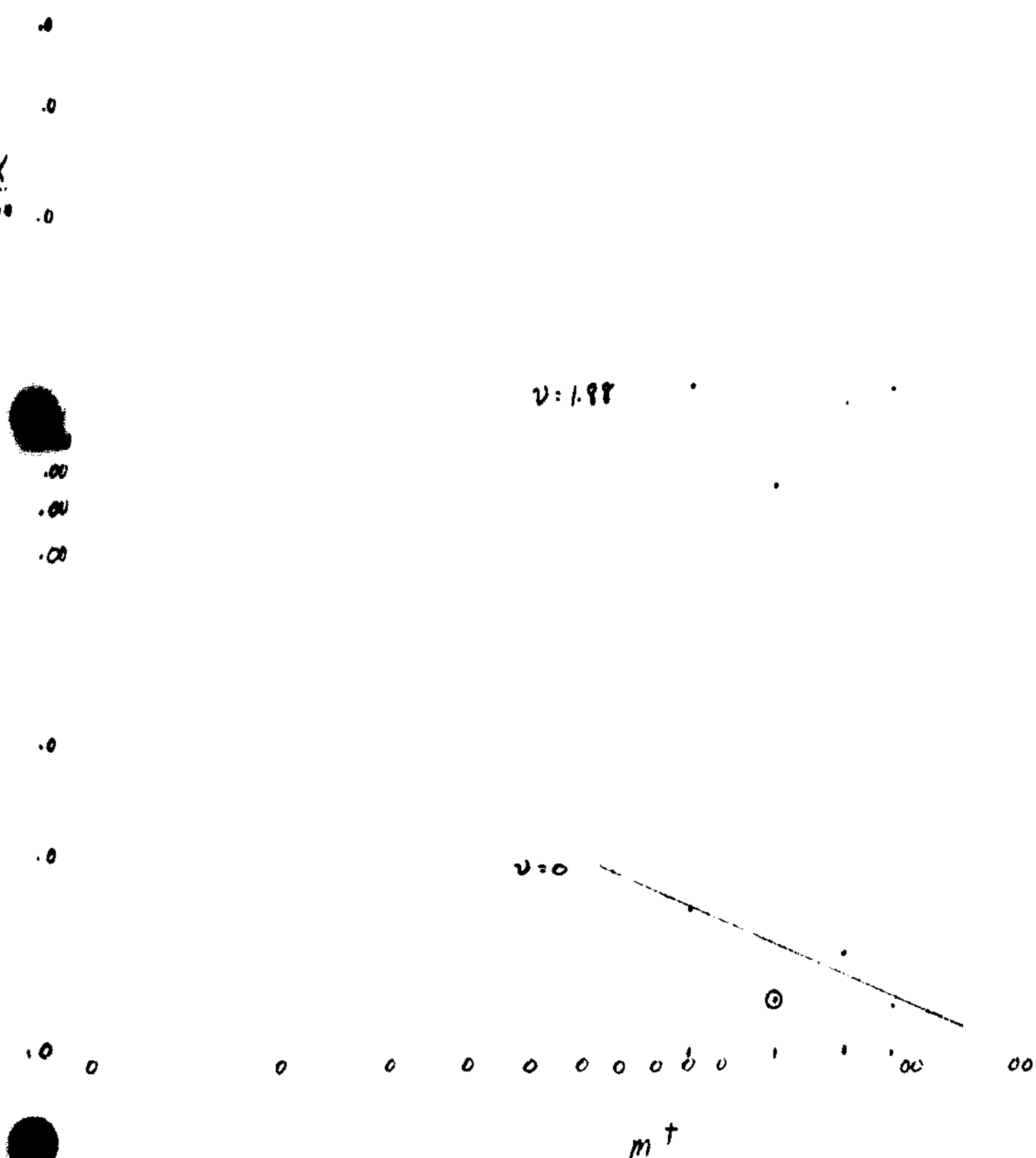
ν	Re	M(ft)	V*(ft/sec)	$K \times 10^3$(ft/sec)	M+	$K/V^* \cdot 10^2$
0	5205	.0083	.194	2.43	131	1.25
	4150	.0073	.182	2.77	108	1.52
	3056	.0061	.166	2.16	82.8	1.30
	2097	.0050	.151	2.69	61.4	1.78

ν	$K \times 10^3$(ft/sec)	M+	$K/V^* \cdot 10^2$	ν	$K \times 10^3$(ft/sec)	M+	$K/V^* \cdot 10^2$
4.39	3.04	131	1.56	1.88	2.25	131	1.16
	3.07	108	1.68		2.02	108	1.11
	3.85	82.8	2.32		1.37	82.8	.825
					1.62	61.4	1.07
7.14	1.83	131	.943	3.25	2.72	131	1.40
	2.21	108	1.21		2.54	108	1.40
	3.18	82.8	1.92		3.68	82.8	2.22

θ : 8.12°

K/V* vs M+ as fct of roll wave frequency (HZ)

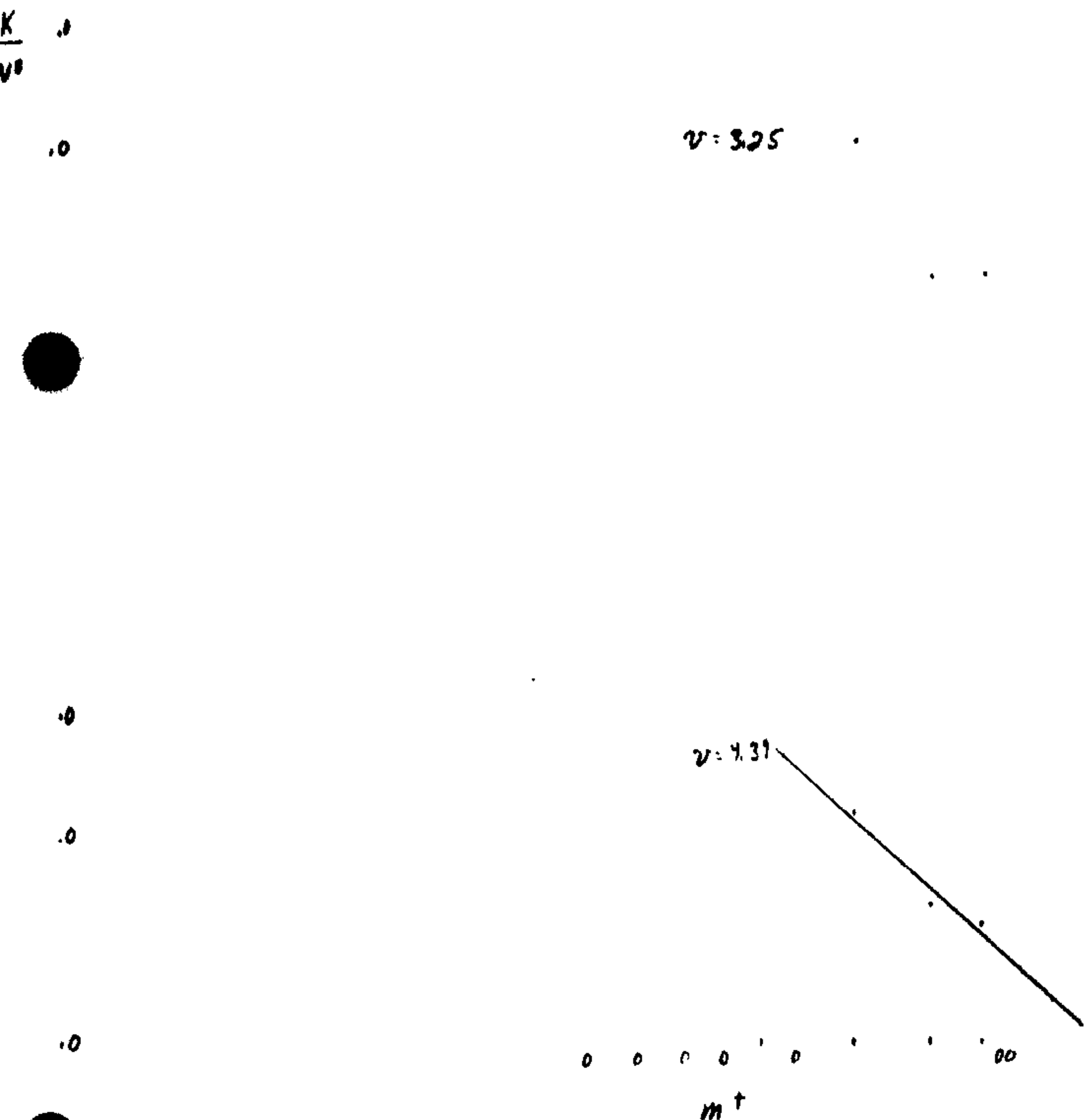
Fig 3



$\theta = 8.12°$

K/V* vs M+ as fct of roll frequency (HZ)

Fig 4



$\theta = 8.12^\circ$

K/V* vs M+ Roll Wave freq.=7.14 HZ

Fig 5

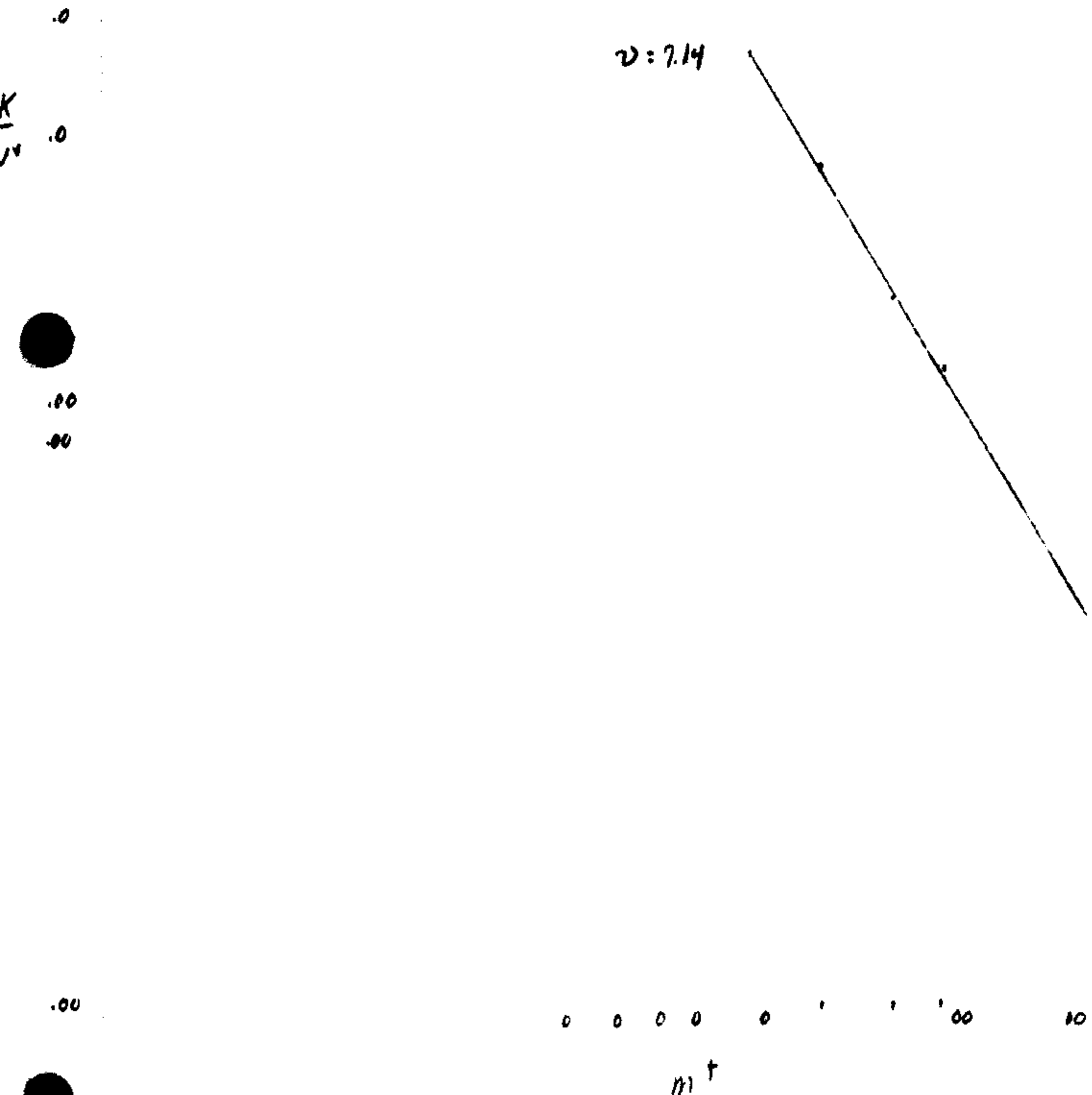


TABLE 9

$\theta = 10.05^{\circ}$

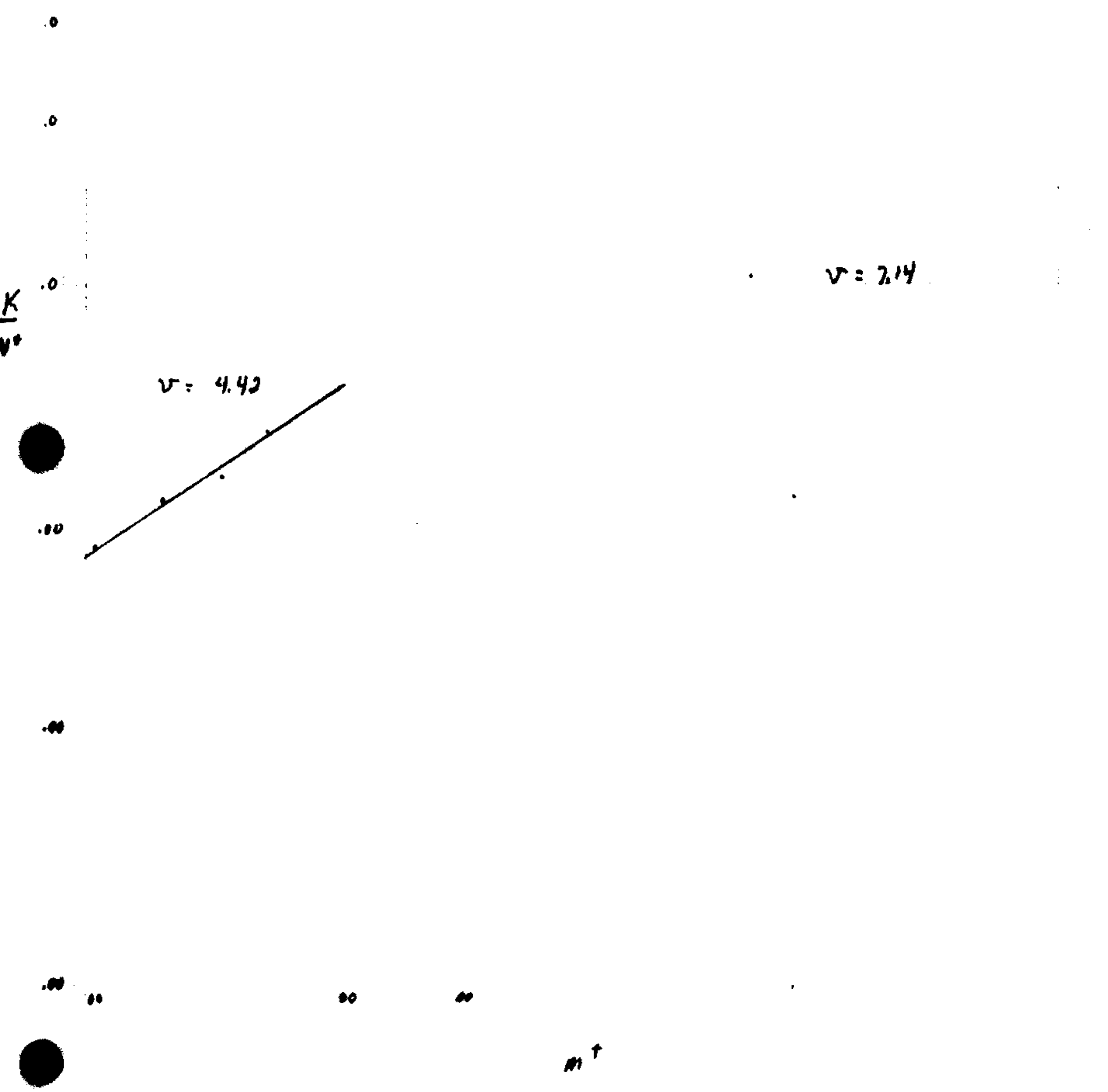
ν	Re	M(ft)	V^*(ft/sec)	$K \times 10^3$(ft/sec)	M+	$K/V^* . 10^3$
0	5205	.0082	.215	1.55	143	7.22
	4150	.0071	.200	1.41	116	7.06
	3056	.0060	.184	1.46	89.7	7.96
	2097	.0049	.166	0.944	66.2	5.69

ν	$K \times 10^3$(ft/sec)	M+	$K/V^* . 10^3$	ν	$K \times 10^3$(ft/sec)	M+	$K/V^* . 10^3$
1.39	1.38	143	6.42	1.71	1.03	143	4.79
	1.19	116	5.95		.889	116	4.44
	1.11	89.7	6.03		.716	89.7	3.89
	1.16	66.2	6.99		.712	66.2	4.29
2.98	1.39	143	6.46	4.42	2.44	143	11.35
	1.19	116	5.95		1.89	116	9.45
	.905	89.7	4.92		1.57	89.7	[illegible].53
	.738	66.2	4.45		1.17	66.2	7.05

$\theta = 10.05$

K/V* vs M+ as fct of Roll Wave Frequency (HZ)

Fig 6



$\theta = 10.05$

K/V* vs M+ as fct of Roll Wave Frequency (HZ)

Fig 7

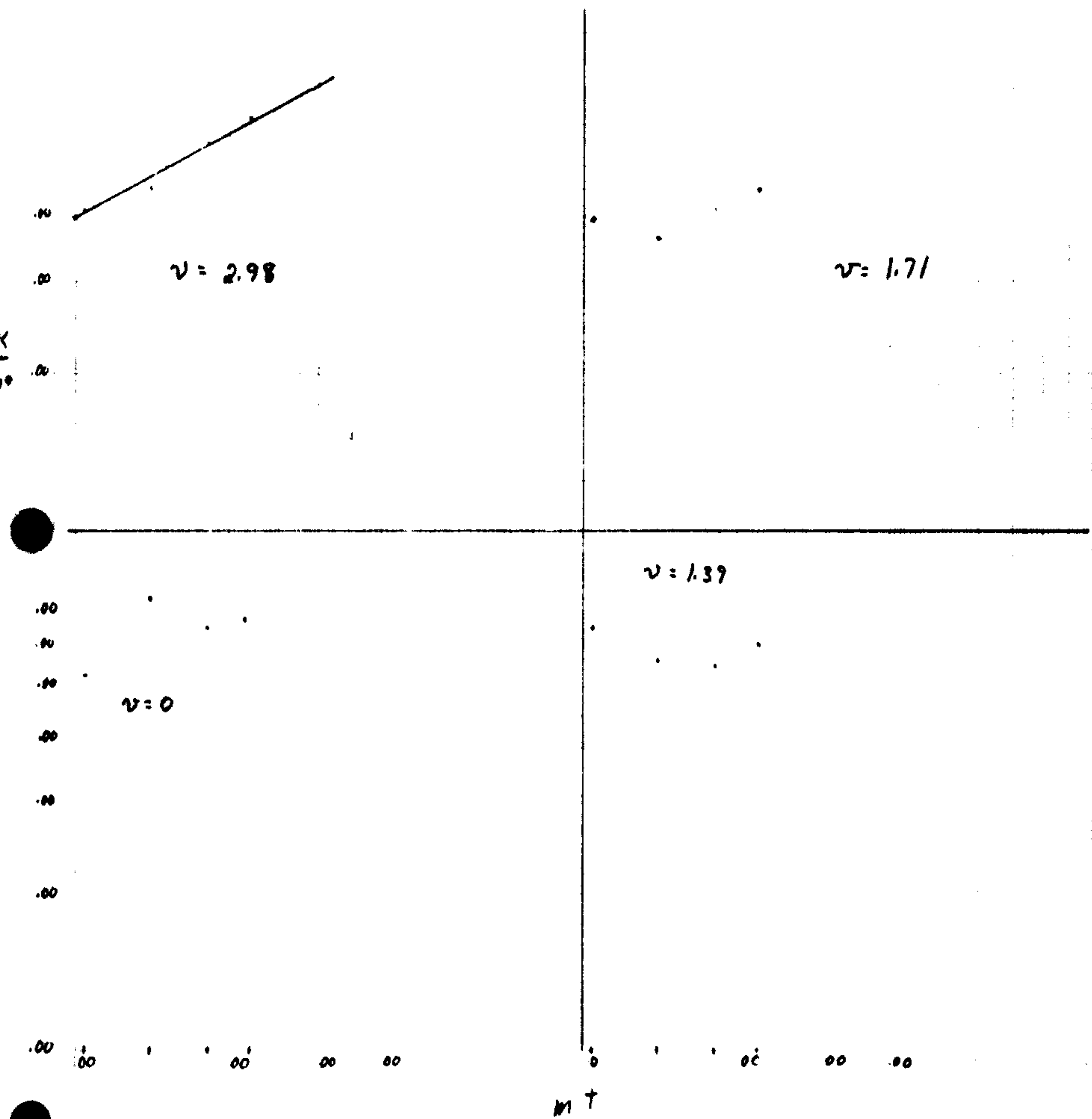


TABLE 10

$\theta = 12.04^{\circ}$

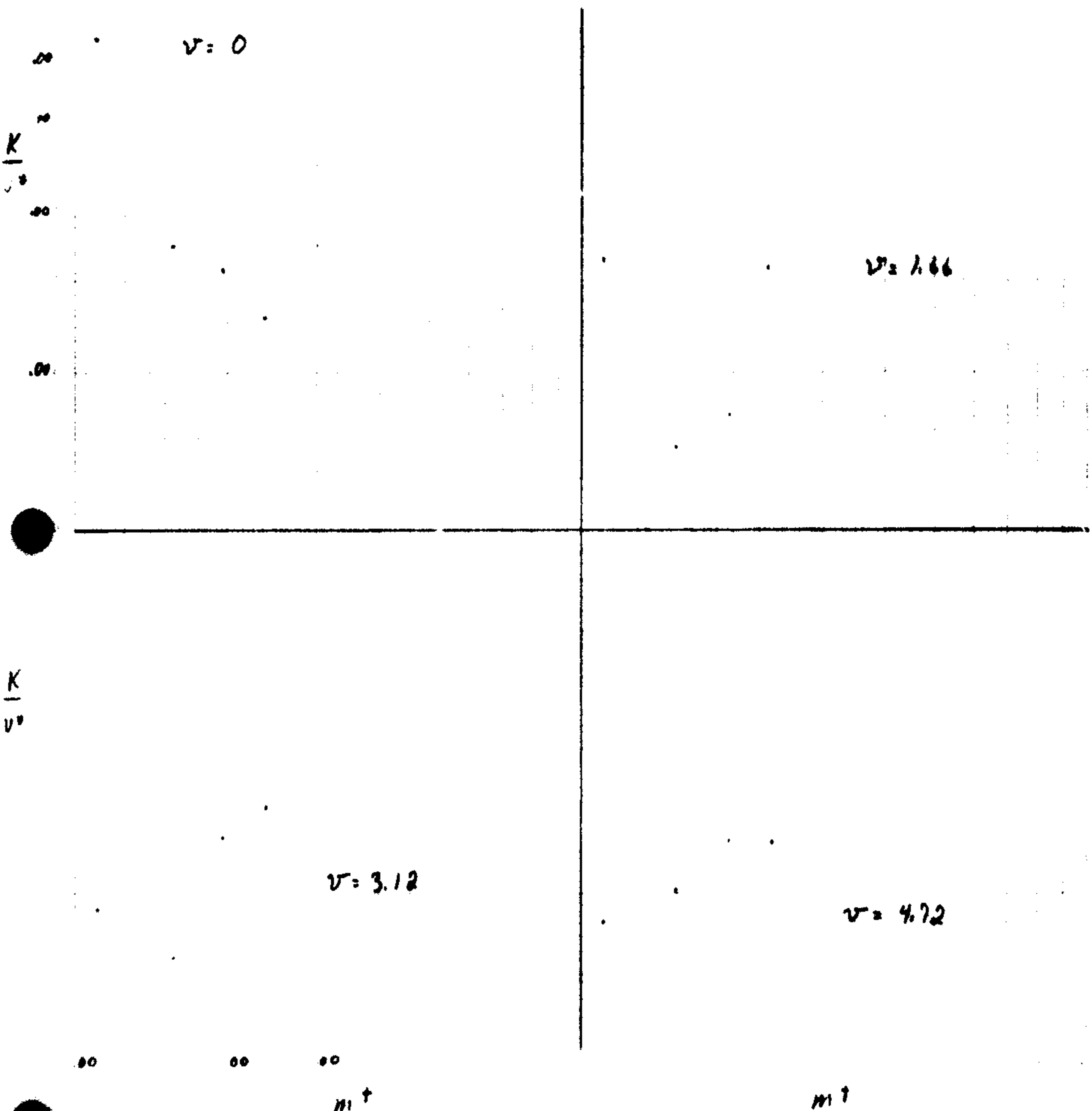
ν	Re	M(ft)	V*(ft/sec)	K×10^3(ft/sec)	M+	K/V*.10^3
0	5205	.0081	.233	.638	154	2.74
	4150	.0071	.218	.735	126	3.37
	3056	.0060	.201	.758	98.13	3.78
	2097	.0049	.181	1.69	72.42	9.32

ν	K×10^3(ft/sec)	M+	K/V*.10^3	ν	K×10^3(ft/sec)	M+	K/V*.10^3
1.66	.795	154	3.41	3.12	.733	154	3.15
	.391	126	1.79		.599	126	2.75
	.310	98.13	1.54		.326	98.13	1.62
	.558	72.42	3.08		.362	72.42	2.00
4.72	.712	154	3.06	5.62	.957	154	4.11
	.595	126	2.73		.704	126	3.23
	.441	98.13	2.19		.602	98.13	3.00
	.342	72.42	1.89		.395	72.42	2.18
7.14	1.39	154	5.97				
	1.16	126	5.32				
	1.18	98.13	5.87				
	0.838	72.42	4.63				

θ = 12.04

K/V* vs M+ as fct of Roll Wave Frequency (HZ)

Fig 8



θ = 12.04°

K/V* vs M+ as fct of Roll Wave Frequency (HZ)

Fig 9

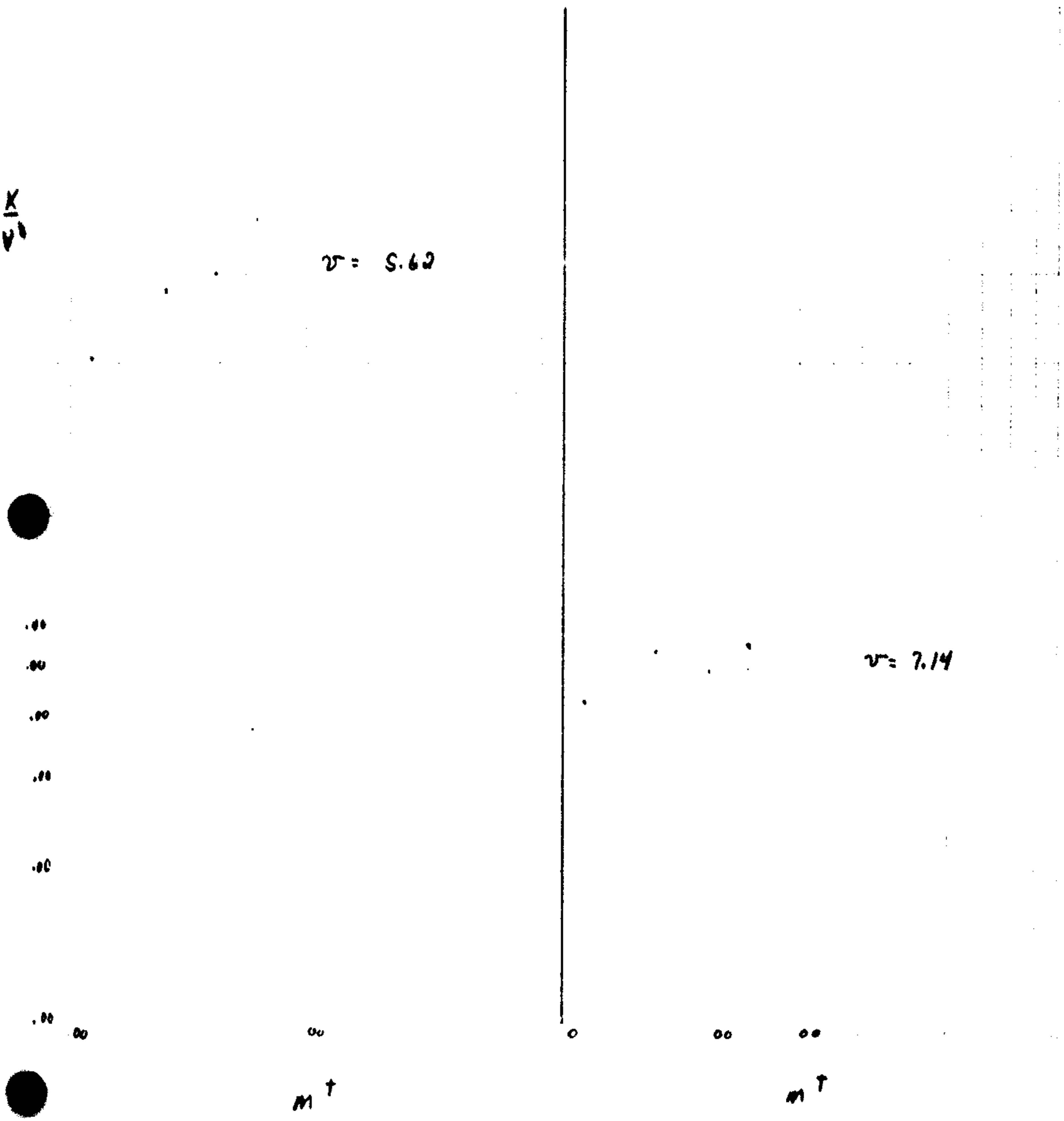


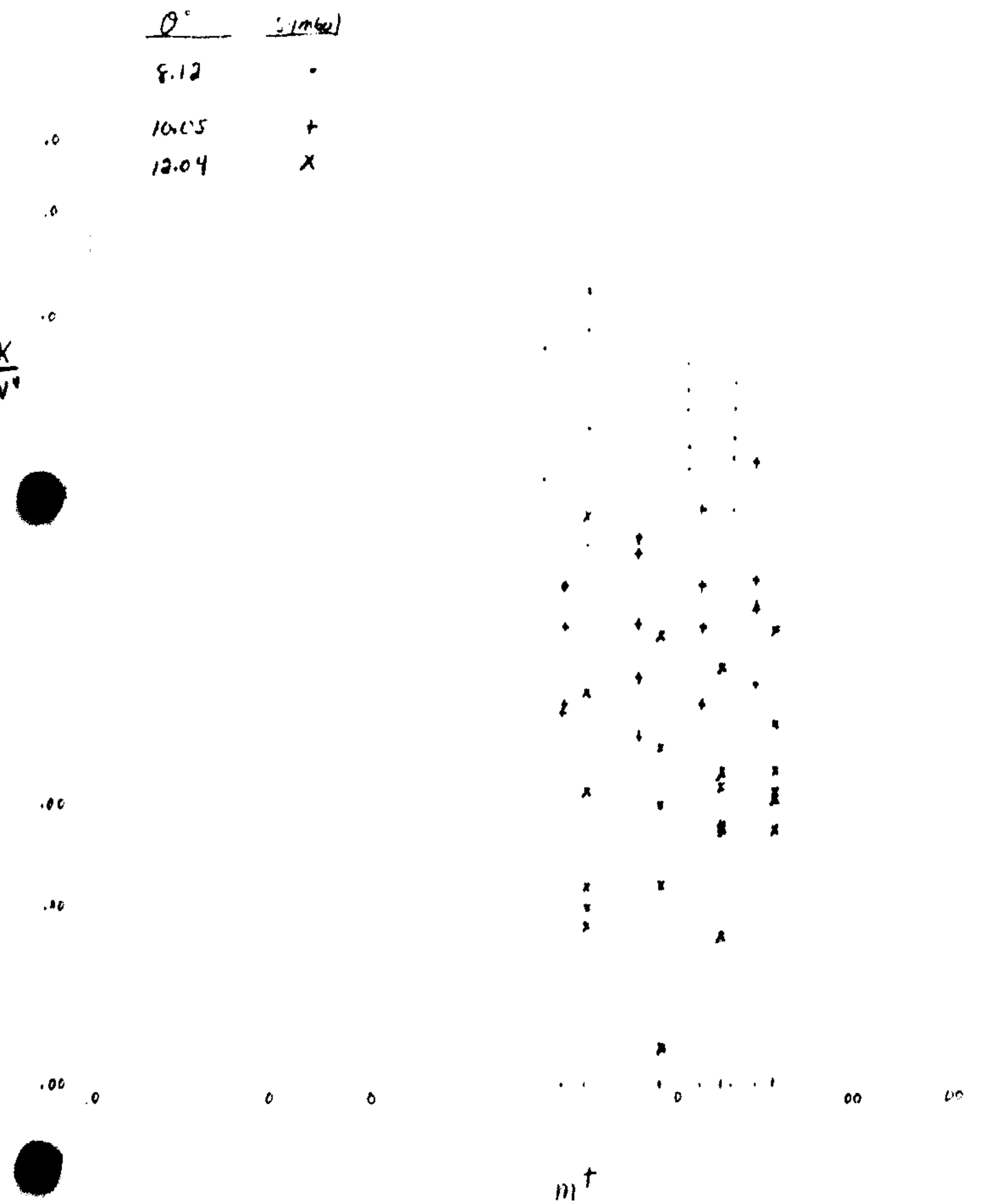
TABLE 11 M+

K/V*.10^2, θ

θ M+	8.12	10.05	12.04
61.4	1.07,1.78		
66.2		.596,.429,.699 .445,.705	
72.4			.932,.200,.308 .218,.189,.463
82.8	.825,1.30,2.[illegible]3 1.92,2.22		
89.7		.796,.389,.603 .853,.492	
98.1			.378,.162,.154 .300,.219,.587
108	1.52,1.11,1.6[illegible] 1.21,1.40		
116		.706,.444,.595 .945,.59[illegible]	
126			.337,.275,.179 .323,.273,.532
131	1.25,1.16,1.[illegible]6 .943,1.40		
143		.722,.479,.642 1.14,.646	
154			.274,.315,.341 .411,.306,.597

K/V* vs M+ at Different Inclinations

Fig 10



Logarithmic, 2 x 2 Cycles

TABLE 12

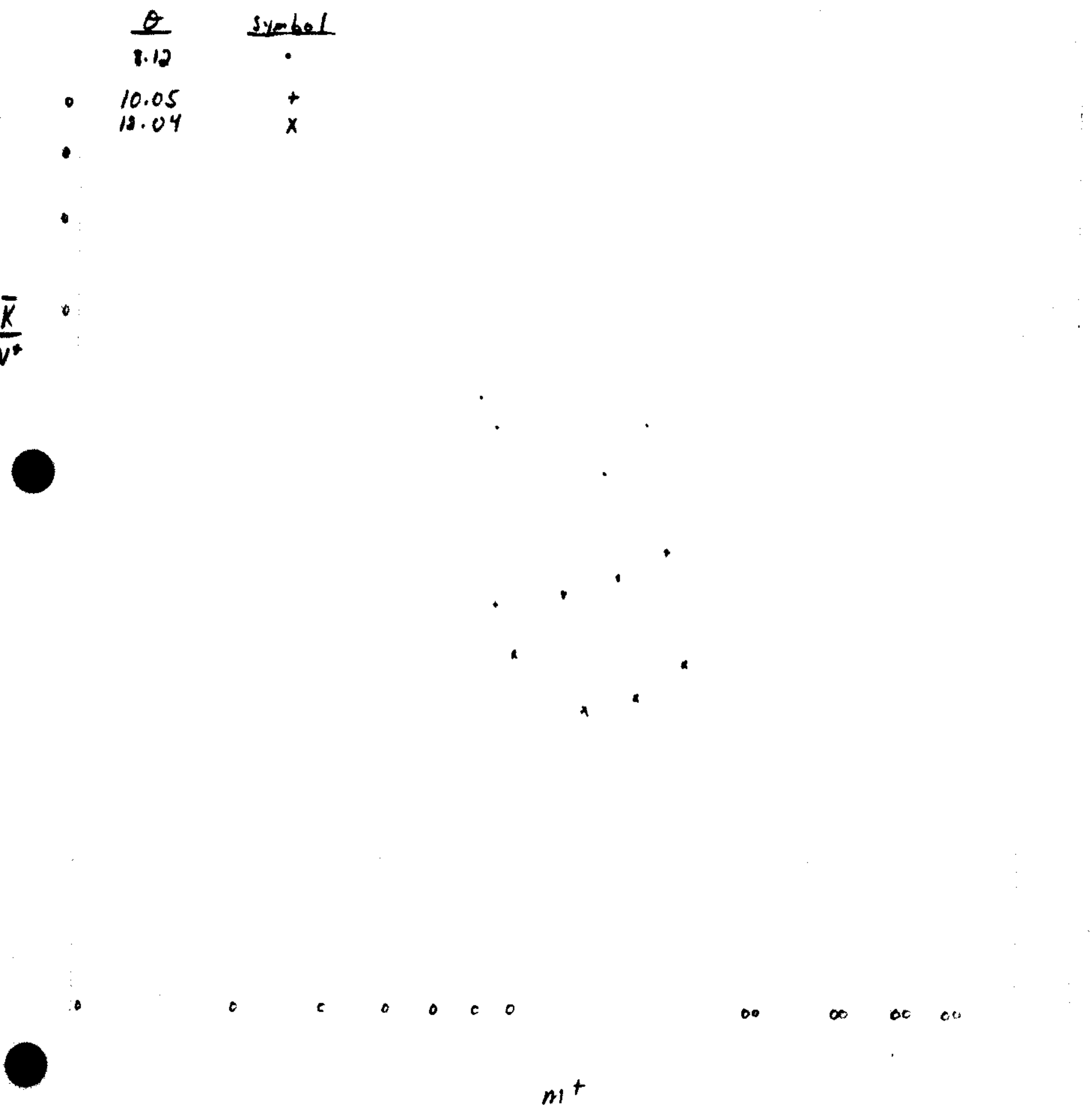
Average values of K/V* for all wave frequencies

M+, $\overline{\frac{K\times10^3}{V^*}}$, θ

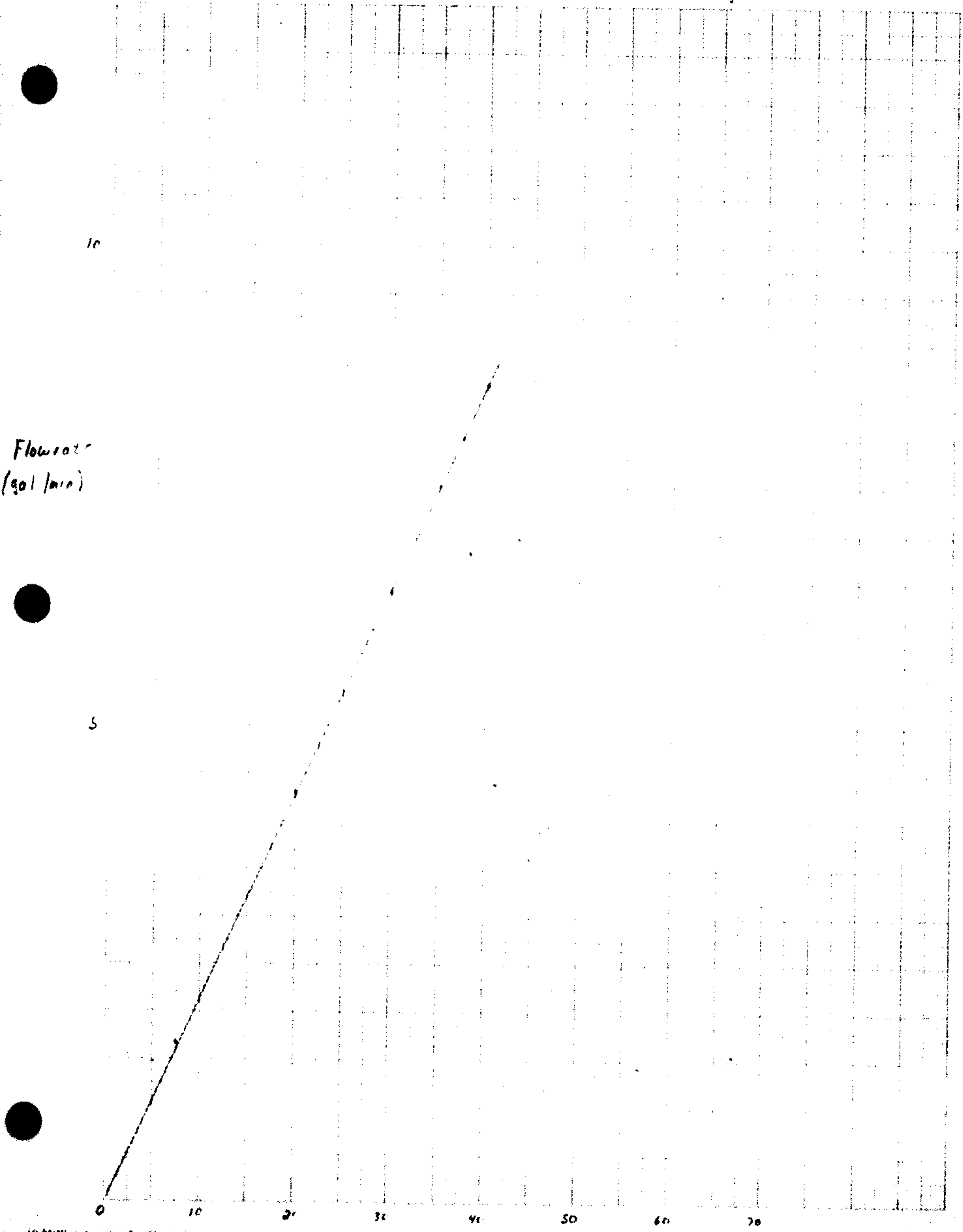
θ M+	8.12	10.05	12.04
61.4	14.3		
66.2		5.69	
72.4			4.62
82.8	12.5		
89.7		6.25	
98.1			3.60
108	10.5		
116		6.55	
126			3.84
131	12.6		
143		7.26	
154			4.46

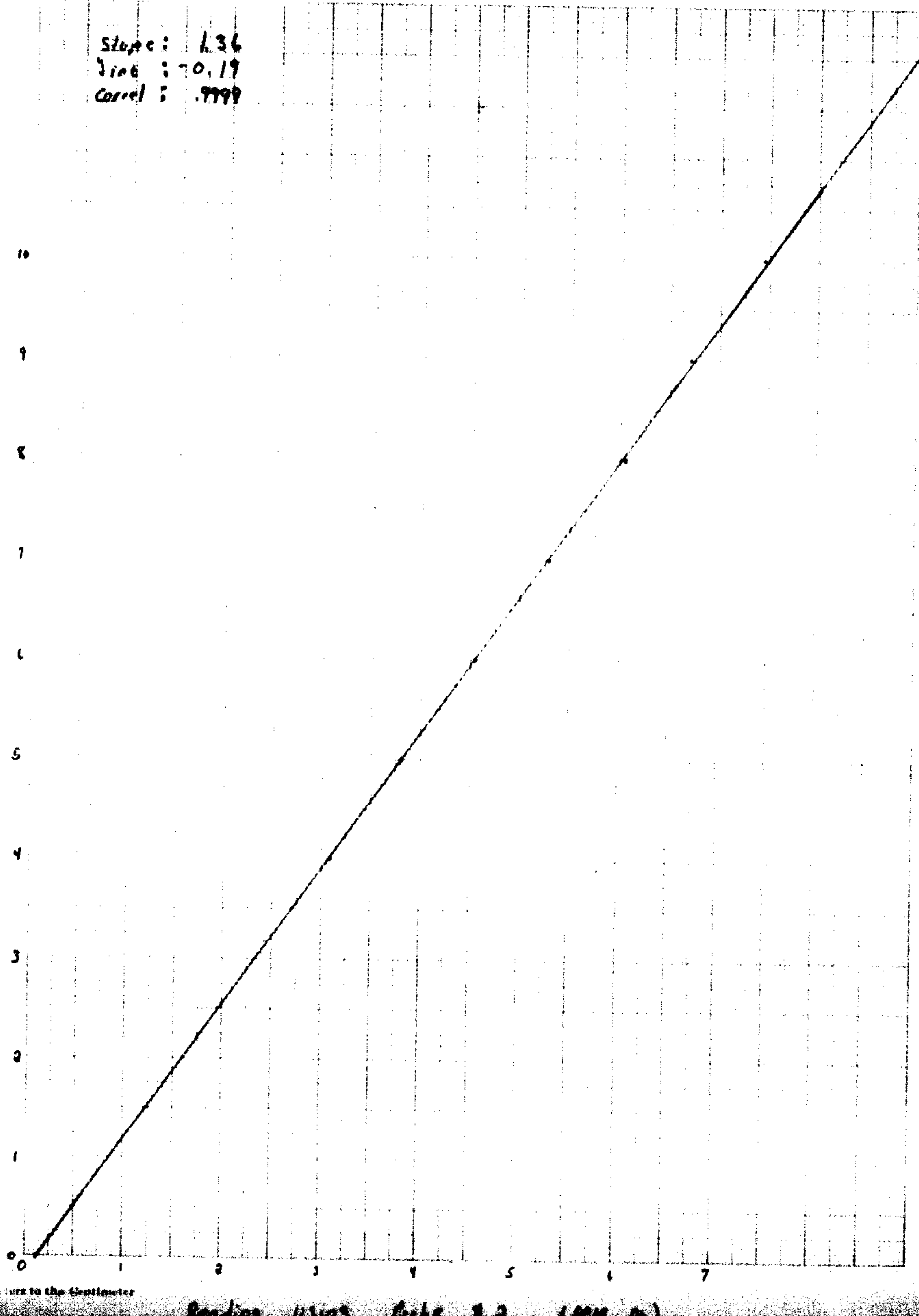
Fig 11

Average K/V* vs M+ for Different Inclinations

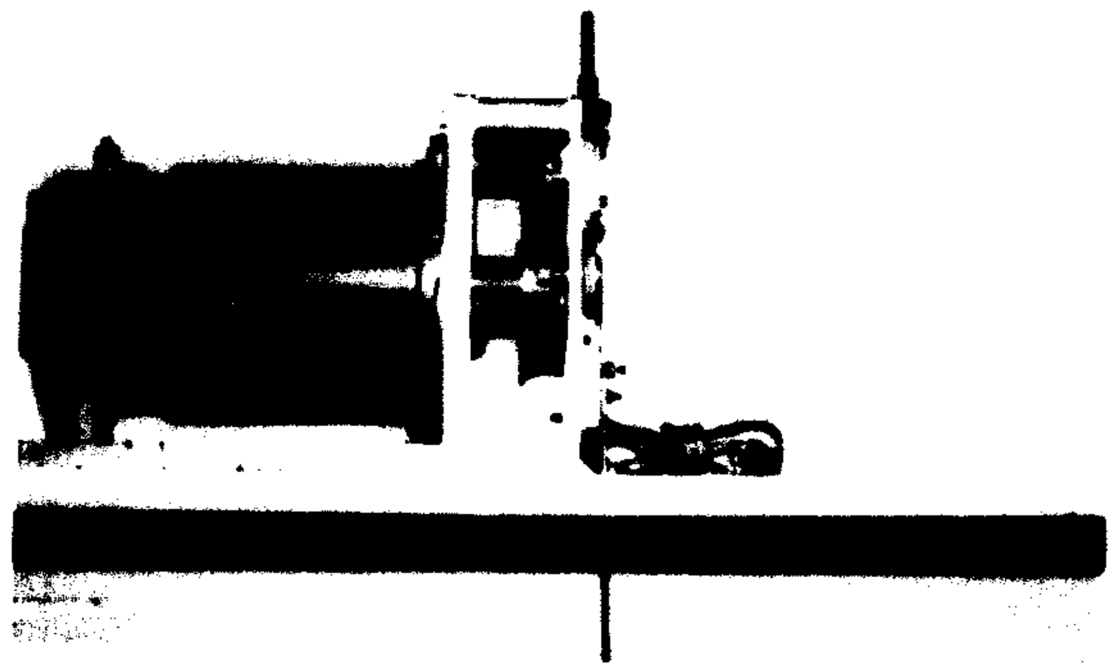


Rotameter Calibration Fig 12

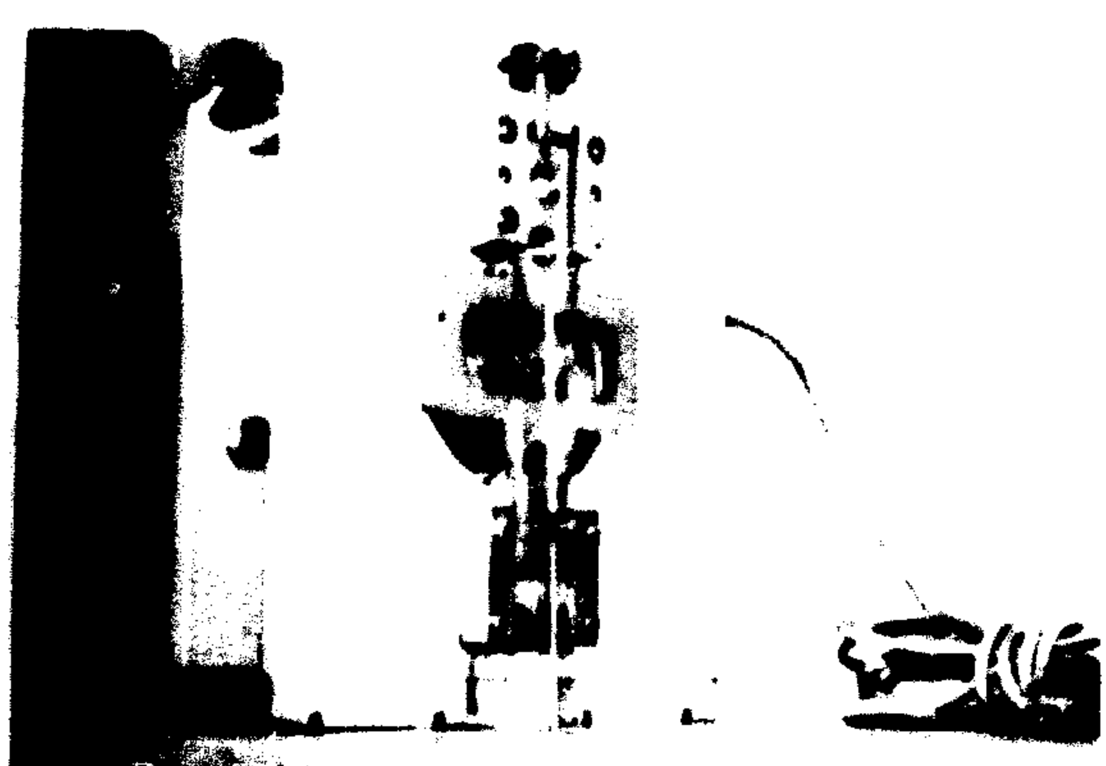



Slope: 1.36
Int: -0.19
Correl: .9999
Reading Using Probe #1 (ppm O_2)
Reading Using Probe #2 (ppm O_2)
0
1
2
3
4
5
6
7
8
9
10

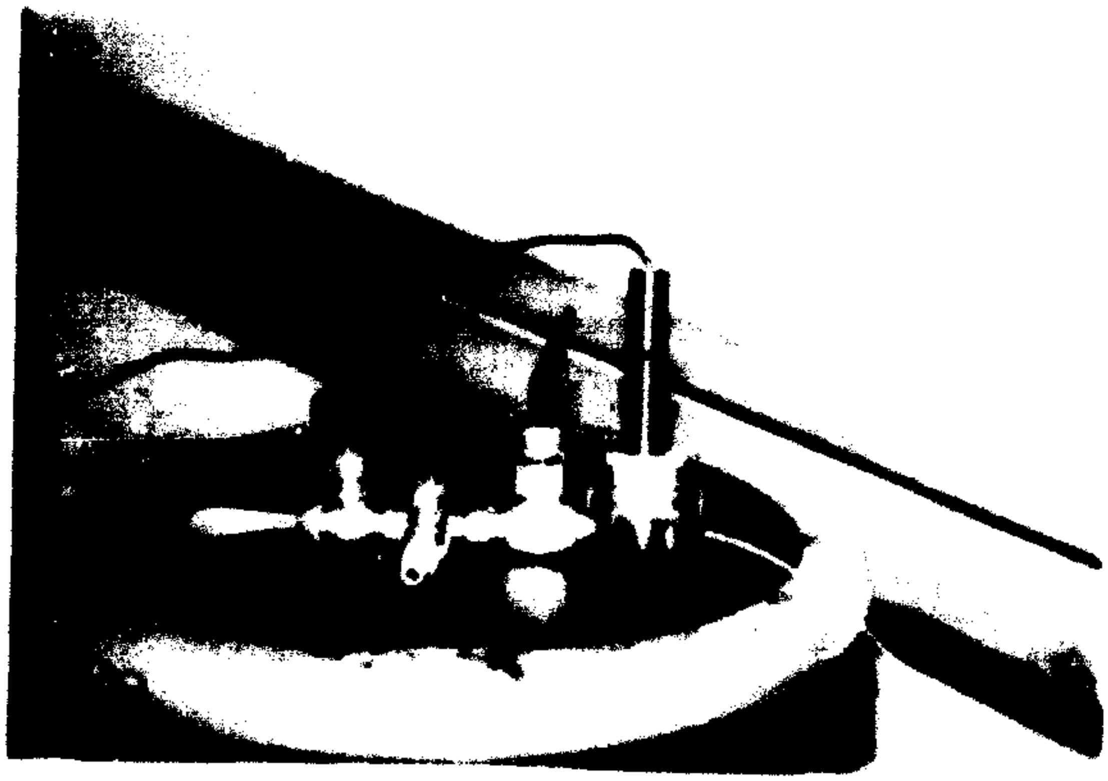
Photograph 1 Motor and Cam (side view)



Photograph 2 Motor and Cam (front view)



Photograph 3 Electrode Network



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